Session C3: Signals of Opportunity-Based Navigation Systems 1

LTE transmitter states estimation using a combined code and carrier phase observation model

Muhammad S. Hameed, Markel Arizabaleta-Diez, Mathias Philips-Blum and Thomas Pany

Universität der Bundeswehr München
Overview - State of the Art with LTE/5G Positioning

**LTE Positioning**

- **Network Based**
  - Standardized in LTE Release 9 with Positioning Reference Signal (PRS) [1].
  - Dedicated resource allocation [2][3]:
    - Requires additional bandwidth → constraint on provider
    - Cellular provider specific → not transmitted by all providers
    - User position shared with network → privacy compromised

- **UE Based**
  - Based on TOA estimation using synchronization and dedicated signal resources e.g. PSS, SSS and CRS.
  - TOA estimation (advanced signal processing) techniques [4]:
    - First peak detection technique
    - Statistical modeling of CIR
    - Super-resolution algorithm
    - Delay-lock loop
  - SOTA LTE receiver [3][5]:
    1. Acquisition and tracking of LTE using PSS and SSS
    2. Obtain first estimate of TOA using SSS
    3. Update of TOA estimate based on CIR estimated using CRS

**5G Positioning**

- Indoor Positioning
  - Extension of TOA estimation for indoor environments.
  - Mixed Line-Of-Sight (LOS) / Non-Line-Of-Sight (NLOS) environment.
  - Reducing NLOS errors through [6]:
    - Smart selection of base station [7]
    - Virtual base station mapping for NLOS signals [8]
    - NLOS propagation model compensation [9]

**State-of-the-art LTE receiver for positioning** [8]

*Urban canyon to indoor positioning evolution*

*Vehicle-mounted receiver’s GPS trajectory and trajectories estimated with LTE SSS and CRS signals [5]*
**LTE signal introduction and MuSNAT implementation**

- **LTE tracking approach** -> generation of a single time-domain replica of the LTE SSS or CRS signal and using conventional GNSS-like DLL, PLL and FLL tracking.

- Code tracking achieved by cross-correlating measured signal with SSS/CRS code replica for complete LTE frame length (= 10 ms)

---

Each ‘vertical’ thin line represents an OFDM symbol of duration 66.6 us.
SSS vs CRS signal comparison

Transition from SSS based tracking to CRS based tracking

Pros:
• Higher bandwidth → narrower correlation peak → low tracking jitter
• Less Doppler side-peaks

Cons:
• More secondary peaks in code phase domain → solvable using BumpJump

[10,11]
LTE transmitter localization - Context

- Simultaneous Localization And Mapping (SLAM) using cellular signals as Signal Of Opportunity (SoP).

- Use of carrier phase of LTE has been previously investigated within:
  - Differential navigation framework with Base/Navigator for:
    - indoor environments [12]
    - UAV navigation [13]
  - Absolute positioning framework leveraging frequency stability of LTE base station clocks for UAV navigation [13]

- Experimental results published so far assume an a-priori known transmitter position obtained beforehand through a collaborative mapping [14] of the transmitter.

- With dynamic receivers or UAVs → estimation of transmitter states with carrier phase measurements can potentially be realized.

- The ‘knowledge’ of transmitter states can be broadcasted as part of pseudolite signals in future.
Filter setup and simulation results

Localization filter set-up $\rightarrow$ a six states Kalman Filter using code and carrier phase LTE measurements

\[
\begin{align*}
    x &= \begin{pmatrix} \hat{N}^2 \\ N^2 \delta T^2 \\ \delta T^4 \end{pmatrix} \\
    y &= \begin{pmatrix} \hat{N} \\ \delta N \\ \delta \delta N \end{pmatrix} \\
    B &= \text{diag}[1_{4\times4}, B_{\text{clk}}]^	ext{T} \\
    B_{\text{clk}} &= \begin{pmatrix} 1 \\ 0 \\ 0 \\
        0 \\ 0 \\ 0 \\
        0 \\ 0 \\ 0 \\
        0 \\ 0 \\ 0 \end{pmatrix} \\
    H &= \begin{pmatrix} -(\delta \delta T)^	ext{T} \\ 0 & -c \\ -(\delta T)^	ext{T} \\ 0 & -c \end{pmatrix} \\
    P_{0} &= \text{diag}(\sigma_{\delta N}^2, \sigma_{\delta \delta N}^2, \sigma_{\delta \delta \delta N}^2, \sigma_{\delta T}^2, \sigma_{\delta \delta T}^2, \sigma_{\delta \delta \delta T}^2) \\
    R &= \text{diag}(\sigma_{\delta T}^2, \sigma_{\delta \delta T}^2) \\
    Q &= \text{diag}(\Omega_{\delta T}^2, \Omega_{\delta \delta T}^2, \Omega_{\delta \delta \delta T}^2, \Omega_{T}^2, Q_{\text{clk}})^	ext{T} \\
    Q_{\text{clk}} &= \begin{pmatrix} S_{\text{clk}}T + S_{\text{clk}}^2T^2 & \frac{3}{2}S_{\text{clk}}T^2 & S_{\text{clk}}T^3 & S_{\text{clk}}T^2 \\
        \frac{3}{2}S_{\text{clk}}T^2 & S_{\text{clk}}T^3 & S_{\text{clk}}T^4 & S_{\text{clk}}T^3 \end{pmatrix} \\
    \text{KF states} &= [\text{PosX, PosY, PosZ, floatAmbi, clkBias, clkDrift}] \\
    \text{Kalman Filter Time Update} \\
    x_t &= y_t - Hx_{t-1} \\
    P_t &= B P_{t-1} B^	ext{T} + Q \\
    \text{Kalman Filter Measurement Update} \\
    K_t &= P_t H (H P_t H^	ext{T} + R)^{-1} \\
    x_t^\text{\ddagger} &= x_t + K_t y_t \\
    P_t^\text{\ddagger} &= (I - K_t H) P_t
\end{align*}
\]

Estimation of carrier phase float ambiguity allows to use carrier phase for LTE transmitter localization.
Experimental set-up for real-signals

Ground vehicle – VW Transporter
Measurement Bus

Hardware set-up

Processing chain for real signal

UAV - DJI Matrice 600 Pro drone

USRP 2974 IV-curve with DC-DC converter

IEEE/ION PLANS 2023 – April 24-27
Target base station – Amarisoft BS

Research oriented BS operated by institute ETTI within UniBW M campus
- PCI 1 at $f_c = 2.665 \text{ GHz}$
- Omni-directional antenna
- No inter-PCI clock bias or MIMO effects

Ground-truth coordinate of Amarisoft BS TX antenna measured for reference using:
- Trimble R10 used for positioning of 02 static points
- Leica MS60 used for triangulation of antenna coordinates

* PosDiff w.r.t Google Maps coordinate: [-29.71, -6.11, -33.78] m
Ground vehicle with code-only measurements

Localization filter results

CMC Time series

CMC plot indicates several cycle-slips for Ground Vehicle

Localization results using code-only measurements

<table>
<thead>
<tr>
<th>State-variable</th>
<th>Symbol</th>
<th>SSS</th>
<th>CRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. diff. X [m]²</td>
<td>Δx</td>
<td>0.758</td>
<td>4.504</td>
</tr>
<tr>
<td>Pos. diff. Y [m]³</td>
<td>Δy</td>
<td>-5.489</td>
<td>0.9852</td>
</tr>
<tr>
<td>Pos. diff. Z [m]⁴</td>
<td>Δz</td>
<td>-7.606</td>
<td>-1.982</td>
</tr>
<tr>
<td>Absolute pos. diff. [m]⁵</td>
<td>Δ</td>
<td>11.56</td>
<td>6.621</td>
</tr>
<tr>
<td>Clock Bias [ns]</td>
<td>δτ</td>
<td>4.496-6</td>
<td>4.496-6</td>
</tr>
<tr>
<td>Clock Drift [m/s]</td>
<td>δν</td>
<td>3.796</td>
<td>2.089</td>
</tr>
</tbody>
</table>

* Pos differences with respect to Google Map coordinates

CRS results are better than SSS results due to more stable signal tracking
UAV with code and carrier phase measurements

- For code + carrier measurements, 03 flights of UAV conducted near Amarisoft BS to sweep as much arc around the BS antenna as possible:
Tracking results of UAV Flight 3

UAV flight trajectory

GNSS RTK results

MuSNAT Tracking Results

Code-minus-carrier

Cycle-slip free pass with low CMC and dynamic receiver → chosen for further analysis with code + carrier phase measurements
Localization results of UAV Flight 3 with code and carrier phase measurements

<table>
<thead>
<tr>
<th>Testcase</th>
<th>$\delta x$ [m]</th>
<th>$\delta y$ [m]</th>
<th>$\delta z$ [m]</th>
<th>norm($\delta_x$, $\delta_y$, $\delta_z$) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Vehicle</td>
<td>0.464</td>
<td>0.010</td>
<td>-2.28</td>
<td>2.33</td>
</tr>
<tr>
<td>UAV Flight 1</td>
<td>0.590</td>
<td>0.226</td>
<td>-1.98</td>
<td>2.08</td>
</tr>
<tr>
<td>UAV Flight 2</td>
<td>0.688</td>
<td>1.29</td>
<td>0.456</td>
<td>1.52</td>
</tr>
<tr>
<td>UAV Flight 3</td>
<td>-0.301</td>
<td>-0.117</td>
<td>-0.779</td>
<td>0.834</td>
</tr>
</tbody>
</table>

Best results achieved with UAV Flight 3 having longest stable carrier-tracking pass duration.

Convergence of carrier phase residuals after backward smoothing.

Filter convergence time ~ 60 secs.
Error sources -> GNSS SPP receiver clock error

- Receiver clock offset gets eliminated in RTK
- For localization → filtered GNSS SPP clock error was used.
- 1\textsuperscript{st} order polynomial fitted on measured receiver clock error
- Alternatively, a more stable on-board clock can be used.

Front-end setup

Residuals of measured receiver clock error w.r.t 1-order polynomial for a static receiver measurement
Conclusions

- LTE signal tracking can be realized in a GNSS oriented tracking architecture.

- CRS provides a better tracking performance with high $C/N_0$ than SSS due to narrower correlation function and more distant Doppler side-peaks.

- Amarisoft Base station serves as a good platform for verifying calibration procedure due to easy access and availability of ground truth.

- It is possible to use carrier phase tracking of LTE signal for the purpose of transmitter localization given an accurate information of the receiver states.

- Efficient cycle-slip detection scheme should be employed.

- With combined code and carrier-phase observations, a position accuracy of within 0.3 m is achieved in North and Up directions and within 1 m in the Up direction for at least one UAV flight.

- One of the biggest error sources is the SPP receiver clock offset.
Way forward

Testcases planned for future:

- Computation of LTE DD observations using two LTE transmitters and two receivers
- Evaluation of code and carrier phase noise of LTE CRS as function of carrier-to-noise ratio
- Comparison of code and carrier phase noise for Ground Vehicle and UAV receiver platforms
- Localization of LTE transmitter through a UAV receiver platform with on-board atomic clock
- Precise localization of LTE transmitter using LTE DD observations
- Differential positioning of a Ground Vehicle with GNSS and one LTE signal using a-priori known LTE transmitter position
References

[1] Release 9 (3gpp.org)
[10] M. Hameed, M. Arizabaleta, T. Pany, LTE transmitter position estimation through combined GNSS and LTE tracking using a software receiver, NAVITEC, 2022
Contact:

Muhammad S. Hameed, M.Sc.

Institute of Space Technology and Space Applications

Universität der Bundeswehr München

Email: muhammad.hameed@unibw.de

Phone: +49 (0)89 6004 4156